An Onboard Scientist for Multi-Rover Scientific Investigation

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MISUS: Multi-Rover Integrated Science Understanding System

Goal: Provide an “onboard scientist” capability to a team of rovers. Enable the team to investigate a new environment in a closed-loop, autonomous fashion with little communication from ground.

Objectives:

- Integrate AI machine learning and planning techniques to provide closed-loop data collection, analysis and sequence generation.
- Intelligently coordinate multiple rovers in performing science operations both at command level and science analysis level.

Key Innovations:

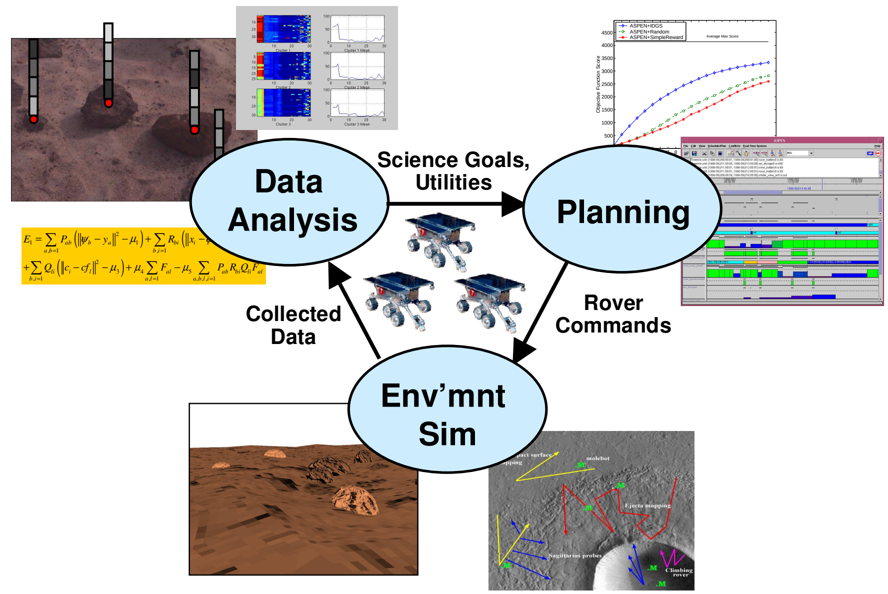
- Develop strategies for interdependent science-goal selection and successful achievement
- Enable continuous science, where new data is iteratively analyzed and changing science objectives are reflected in team schedule

NASA Relevance:

- Enabling to future missions that utilize larger and smarter sets of rovers to gather science data.
- Also applicable to spacecraft and/or constellation missions that would benefit from onboard data analysis

Accomplishments to date:

- Developed new data analysis algorithm for evaluating measurement uncertainty and science goal relationships
- Developed planning optimization approach for handling interdependent science-goal utilities
- Developed distributed planning capability for re-assigning science goals due to unexpected failures
- Extended environment simulation to incorporate more realistic mineralogical distribution



System Description:

- ***Data Analysis:*** A machine-learning system that analyzes input visual and spectral data, and prioritizes new science targets.
- ***Planning:*** A distributed, continuous planning system that produces rover operation plans to achieve input science goals.
- ***Environment Simulation:*** A multi-rover simulator that models geological environments and rover science activities within them.

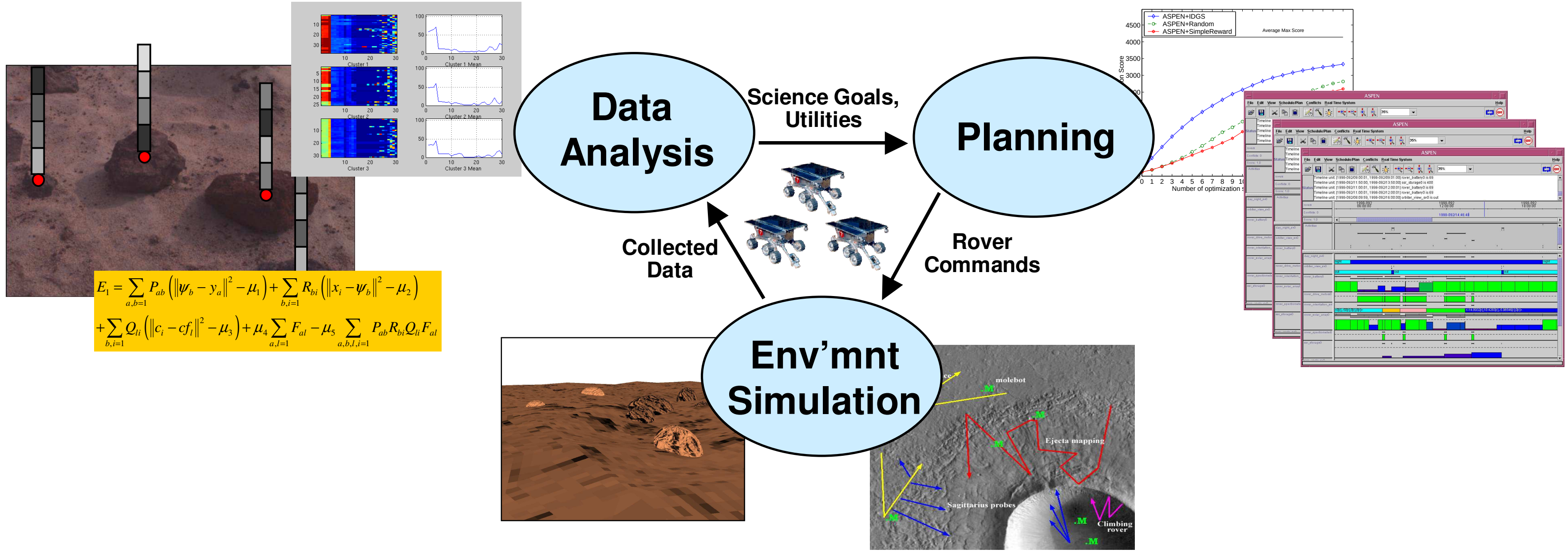
Schedule:

- FY01: Develop centralized scheduling of interdependent subgoals. Develop analysis algorithm for evaluating goal relationships.
- FY02: Develop distributed scheduling of interdependent science goals. Implement analysis algorithm. Integrate rock-patch-facies-deposit terrain model.
- FY03: Enable continuous science goal evaluation and integration into rover schedule. Evaluate full system on field data.

MISUS Approach

- Framework for coordinating multiple rovers in performing autonomous science operations
  - Provides "onboard scientist" capability
  - Enables rover team to autonomously investigate new environment
- System integrates techniques from machine learning and planning/scheduling
  - Data analysis
  - Generates new science goals
  - Produces valid plans to achieve goals
  - Monitors plan execution and performs re-planning
- Also integrated with a simulation environment that models planetary terrain
- ***Key feature:*** closes the loop between sensor data collection, science goal selection, and activity planning and scheduling

System Overview



1. ***Data Analysis:***
   - Machine-learning clustering system
   - Analyzes input data and constructs summary model
   - Generates and prioritizes new science targets
2. ***Planning:***
   - Distributed, continuous planning system
   - Produces rover operation plans to achieve input science goals
   - Monitors plan execution and re-plans when necessary
3. ***Environment Simulation:***
   - Models geological environments and multiple rover science activites within them

Key Research Objectives

- Interdependent Science Goals
  - Science goals/objectives are typically considered independently
  - Goals are often related – science utility of a goal can increase/decrease if related goals are achieved
  - Investigating methods for reasoning about these interdependent relations to both generate better goals and higher quality plans
- Continuous Science
  - In past work, science analysis and plan generation/execution has been performed at separate intervals
  - Investigating methods to continuously update data models and re-evaluate current science objectives
  - Also extending planning system to continuously accept new science goals or changes to current goals and modify plan accordingly

Recent Accomplishments

- Implemented a novel clustering approach that clusters in heterogeneous feature space
  - Employs an objective function for inferring geological relationships among data
  - Both spectral and visual texture data are analyzed
- Developed a new prioritization algorithm that uses clustering output to generate a new set of observation goals
  - New information will further improve accuracy of data model
  - Select goals based on evaluation of scientific importance
  - Algorithm examines and outputs goal interdependency relations
- Developed a goal interdependency representation language
  - Enables goal dependencies and related utilities to be communicated to planning system

Recent Accomplishments, cont.

- Developed planning optimization approach for reasoning about interdependent goal relations
  - Evaluates goal interdependency relations when selecting subset of goals to achieve
  - Optimization based on randomized hill-climbing with restart
  - Shown to significantly improve plan quality
- Developed approach for re-assigning science goals to new rovers
  - Failure or unexpected resource over-subscription may cause some assigned goals to be unachievable
  - Planning system dynamically assigns goals to other rovers if possible
  - Uses SHaC approach to coordinating shared activities among multiple agents (Clement, 2002)

Recent Accomplishments, cont.

- Revamped environment simulator to incorporate more realistic terrain distribution
  - Based on rock-patch-facies-deposit environment model of mineralogical deposits (Fink, 2001).
- Gathered new suite of mineralogical data at field site near Baker, CA.
  - Selected site with two distinct deposits and boundary area
  - Collected both image and point spectrometer data
  - Will be used to populate environment simulator model for system testing

Current and Future Directions

- Enable continuous science data evaluation and goal generation
  - Extend data analysis algorithm to iteratively evaluate science data and continuously adjust science priorities
- Enable iterative schedule integration of new science goals
  - Currently goals are received and planned for in batch fashion
  - Extend planning system to handling continuously changing science objectives
- Increase distributed capabilities to support limited communication
  - Extend new data analysis algorithms to operate in distributed fashion that reduces communication overhead between rovers
  - Extend distributed planning system to operate with limited communication opportunities
- Perform extensive system evaluation
  - Use both data from field site collections and from USGS and ASTER databases
  - Evaluate overall system performance in correctly identifying deposits
  - Evaluate individual performance of data analysis and planning components

Extra Slides

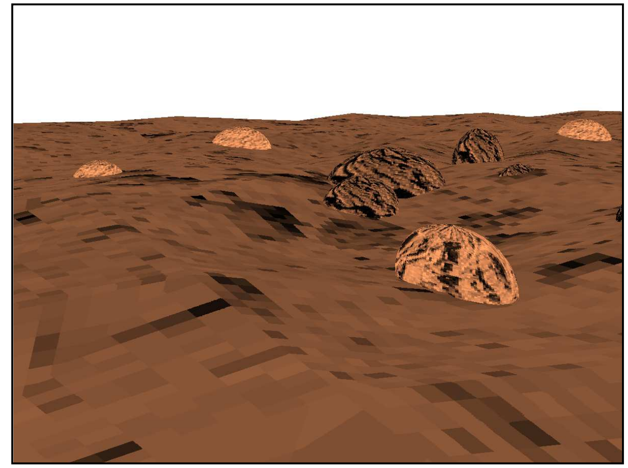
Science Data Analysis

- Models distribution of rock types in the observed terrain
- Uses a novel clustering approach that allows features to be treated heterogeneously
  - Employs an objective function for inferring geological relationships among data
  - Both spectral and visual texture data are analyzed
- A prioritization algorithm uses clustering output to generate a new set of observation goals
  - New information will further improve accuracy of data model
  - Select goals based on evaluation of scientific importance
- Prioritization examines goal interdependency relations
  - Individual goal values may by dependent on related goals being achieved
  - Algorithm generates goals, goal-utility values and goal interdependency relations

Planning

- Uses distributed version of CASPER planning system
  - Central planner develops abstract plan, dividing goals among rovers
  - Individual rover planners develop detailed, executable plan for achieving assigned goals
- Planning system can reason about interdependent goal relations
  - Evaluates goal interdependency relations when selecting subset of goals to achieve
  - Optimization based on randomized hill-climbing with restart
- Planning is dynamic
  - Rover planners monitor plan execution and perform re-planning when necessary
  - Uses rover simulation tool to provide execution feedback
  - Rover goals can be re-assigned to other rovers dynamically due to unexpected failures or resource over-subscription

Environment Simulation



- Simulates science data operations
- Different Martian rockscapes can be created
  – Select different rock types, size and spatial distributions
  – Currently use rock-patch-facies- deposit environment model to create terrain
- Mineral distributions developed in collaboration with JPL geologists
  – Currently using “rock-patch-facies-deposit” model to realistically create terrain
- Simulator executes science operations at appropriate locations and generates sample data
- Returns both spectral data and visual texture data